IP/BBSR/95-26
hep-ph/9503496

PHASE TRANSITION IN THE EARLY UNIVERSE AND CHARGE QUANTIZATION

AFSAR ABBAS
Institute of Physics
Bhubaneswar-751005, India
E-mail : afsar@iopb.ernet.in

Abstract

It is shown, for the first time , that surprisingly the electric charge loses all physical meaning above the electro-weak phase transition temperature. Implications of this discovery in the context of the early universe within the framework of various unified models are discussed.

As the universe expands, it is predicted that it undergoes a series of phase transitions[1, 2] during which the appropriate symmetry breakes down in various stages until it reaches the stage of the electro-weak (EW) symmetry. This is given by the group structure $SU(2)_L \otimes U(1)_Y$. After $t \sim 10^{-10}$ seconds (at $T \sim 10^2$ GeV) the electro-weak phase transition to $U(1)em$ through the Higgs Mechanism takes place. It is the strucure of this phase transition that I look into in this paper. The conclusions drawn here are expected to have a basic and significant impact on the whole early universe scenario including the concept of inflation [3, 4, 5, 6] which is playing such an important role in the present day cosmological scenarios.

The idea of the electro-weak phase transition [1] is that above some critical temperature T_c^{EW} the full electro-weak symmetry $SU(2)_L\otimes U(1)_Y$ is restored. This restoration implies that now the $SU(2)_L$ gauge particles $W^{+,-}$, W^0 and the $U(1)_Y$ gauge particle B_μ becomes massless. In addition all matter particles e, μ, τ, u-quark etc becomes massless too. Any model which is expected to hold at temperatures higher than T_c^{EW} (e.g. GUTs, Supergravity, Superstring etc) had better have this above mentioned property of the EW symmetry. And indeed all the currently available models are compatible with this. Let us ask the question : Is there no other effect associated with the restoration of the electroweak theory above T_c^{EW} ? Below I will point out that indeed there is one. I will discuss a new aspect arising from the restoration of the EW symmetry at T_c^{EW} (which has not been looked into before this work). I will then discuss some implications of this discovery.

Until 1989/1990 it was commonly believed that the electric charge was not quantized in the Standard Model (SM) . This is well documented in review articles and text books (see for example ref. [7]). This lack of charge quantization was considered to be a shortcoming of the SM. It was then found that when one goes beyond the SM, say within the framework of the Grand Unified Theories (GUTs) then the electric charge was automatically quantized [7]. In fact this was thought to be the very first and grand success of the GUTs concept.

In the cosmological context this means that at higher energies (or temperatures) where the GUTs idea would be valid that the electric charge is already quantized. In addition it was an experimental fact that at very low energies the electric charge is also quantized. So at that time it was felt that though the electric charge quantization was not apparent in the SM it had to be put in by hand artificially [7].

But recently it has been demonstrated that the above view was wrong and that the electric charge is actually quantized in the SM [8, 9, 10]. It has to be emphasized that the complete structure of the SM with all it's ingredients (like generation structure, Higgs machanism, mass generation, anomaly cancellation etc) is required to give a rigorous and complete demonstration of the electric charge quantisation in the SM [9, 10]. As we shall require some of the ideas later on in this paper let me summarize the arguments demonstrating the existence of charge quantization in the SM.

Let us start by looking at the first generation of quarks and leptons (u, d, e,ν) and assign them to $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$ representation as follows [9, 10].

$$
\begin{aligned}
q_L &= \begin{pmatrix} u \\ d \end{pmatrix}_L , (3, 2, Y_q) \\
& u_R; (3, 1, Y_u) \\
& d_R; (3, 1, Y_d) \\
l_L &= \begin{pmatrix} \nu \\ e \end{pmatrix}; (1, 2, Y_l) \\
& e_R; (1, 1, Y_e)
\end{aligned} \tag{1}
$$

To keep things as general as possible this brings in five unknown hypercharges.

Let us now define the electric charge in the most general way in terms of the diagonal generators of $SU(2)_L \otimes U(1)_Y$ as

$$Q' = a' I_3 + b' Y \tag{2}$$

We can always scale the electric charge once as $Q = \frac{Q'}{a'}$ and hence ($b = \frac{b'}{a'}$)

$$Q = I_3 + bY \tag{3}$$

In the SM $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$ is spontaniously broken through the Higgs mechanism to the group $SU(3)_c \otimes U(1)_{em}$. In this model the Higgs is assumed to be doublet ϕ with arbitrary hypercharge Y_ϕ. The isospin $I_3 = -\frac{1}{2}$ component of the Higgs develops a nonzero vacuum expectation

value $< \phi >_o$. Since we want the $U(1)_{em}$ generator Q to be unbroken we require $Q < \phi >_o = 0$. This right away fixes b in (3) and we get

$$Q = I_3 + (\frac{1}{2Y_\phi})Y \tag{4}$$

Next one requires that the fermion masses arise through Yukawa coupling and also by demanding that the triangular anomaly cancels (to ensure renormaligability of the theory) (see [9, 10] for details); one obtaines all the unknown hypercharge in terms of the unknown Higgs hypercharge Y_ϕ. Ultimately Y_ϕ is cancelled out and one obtain the correct charge quantization as follows.

$$\begin{aligned}
q_L = \begin{pmatrix} u \\ d \end{pmatrix}_L, Y_q = \frac{Y_\phi}{3}, \\
Q(u) = \frac{2}{3}, Q(d) = \frac{-1}{3} \\
u_R, Y_u = \frac{3}{4}Y_\phi, Q(u_R) = \frac{2}{3} \\
d_R, Y_d = \frac{-2}{3}Y_\phi, Q(d_R) = \frac{-1}{3} \\
l_L = \begin{pmatrix} \nu \\ e \end{pmatrix}, Y_l = -Y_\phi, Q(\nu) = 0, Q(e) = -1 \\
e_R, Y_e = -2Y_\phi, Q(e_R) = -1
\end{aligned} \tag{5}$$

It has been shown [9] that for arbitrary N_c the colour dependence of the electric charge as demanded by the SM is

$$\begin{aligned}
Q(u) = \frac{1}{2}(1 + \frac{1}{N_c}) \\
Q(d) = \frac{1}{2}(-1 + \frac{1}{N_c})
\end{aligned} \tag{6}$$

The implication of this for the Grand Unified Theories has been discussed in ref [11].

One should note that equations (5) and (6) show that contrary to all earlier expectations, the electric charge is quantized in SM. The complete structure of the SM as is, is required to obtain this result on very general

grounds. The SM is the best tested model of particle physics. As long as these assumptions are valid as one goes beyond it one should maintain all the intrinsic properties of it. What has this to say about the early universe scenarios available today ?

Clearly the $U(1)_{em}$ symmetry which arose due to spontaneous symmetry breaking due to a Higgs doublet in the EW symmetry will be lost above T_c^{EW} whence $SU(2)_L \otimes U(1)_{em}$ symmetry would be restored. As is obvious, above T_c^{EW} all the fermions and gauge bosons becomes massless [1, 2]. This properly is well-known and has been incorporated in cosmological models. Here I point out a new phenomenon arising from the restoring of the full EW symmetry .

Note to start with the parameter b and Y in equation (3) in the definition of electric charge were completely unknown. We could lay a handle on 'b' entirely on the basis of the presence of spontaneous symmetry breaking and on ensuring that photon was massless $b = \frac{1}{2Y_\phi}$. Above T_c^{EW} where the EW symmetry is restored there is no spontaneous symmetry breaking and hence the parameter b is completely undetermined. Together 'bY' could be any arbitrary number whatsoever even an irrational number. Within the framework of this model above T_c^{EW} we just cannot define electric charges for a fermion at all. It may be a number which is zero or infinite or an irrational etc. Hence the electric charge given by equation (3) loses any physical meaning all together.This is the new amazing result.

So above T_c^{EW} all the particles have not only become massless, they have forgotten their charges also. It just does not make sense to talk of their charges. The concept of electric charge has been lost. There is no such thing as charge anymore. The photon (which was a linear combination of W^0 and B_μ after spontaneous symmetry breaking) with it's defining vector characterteristic does not exist either. So the conclusion is that there is no elctrodynamics above T_c^{EW}.

Note that the electric charge in the SM was not an elementary or fundamental object at all. In fact it was a secondary quantity defined in terms of the elementary objects I_3 and Y (see equation(3)). So it should not be really surprising to see it loose it's meaning under special circumstances. The same is true of the photon of $U(1)_{em}$. In short $U(1)_{em}$ owes its existence to SSB and looses it's meaning when the full EW symmetry is restored. Interestingly the fact that people have found [12] QED to be inconsistent for

massless fermions is a puzzle no more.

As noted above earlier (prior to 1989/1990) electric charge was quantized in GUTs and this was artificially imposed on SM. Now we have demonstrated that actually electric charge is quantised in SM and when at high temperature the EW symmetry is unbroken, the concept of electric charge does not arise. At those and still higher temperatures [1, 2, 3, 4, 5, 6] extensions like GUTs, Supergravity, Superstrings are believed to be relevant. Earlier electric charge quantisation was thought to be a success of the GUTs idea but now in the light of the new development discussed here, this becomes it's major weakness (note that the GUTs idea is supposed to hold above T_c^{EW}). Similarly for the accepted extensions which have become standard in the current cosmological scenarios this becomes a basic problem too.

In short a particular model which pertains to be valid at temperatures higher than T_c^{EW} is in trouble if it has charge quantization built into it. It is demanding something which the SM does not require. Clearly we have to be extremely wary when we are trying to extend models beyond the SM right to $t \sim 10^{-44}$ seconds.

Clearly the fact that the electric charge loses any physical meaning and it's very existence above T_c^{EW} will have major impact on our models of the early universe. How the presently accepted models and scenarios will change in the light of the new information given here has to be studied carefully.

References

[1] D.A. Kirzhnits and A.D. Linde, Phys. Lett. **42B**, (1972) 471

[2] A. D. Linde, Rep.Prog.Phys. **42**, (1979) 389

[3] A.H. Guth and S.H. Tye, Phys.Rev.Lett. **44**, (1980) 631

[4] A.D. Linde, Phys.Lett. **108B** (1982) 389

[5] A. Albrecht and P. Steinhardt, Phys.Rev.Lett. **49**, (1982) 1220

[6] R. H. Brandenberger, Rev.Mod.Phys. **57**, (1985) 1

[7] T.P. Cheng and L.F.Li, " Gauge Theory of Elementary Particle Physics", Clarendon Press, Oxford, 1988

[8] C. Q. Geng and R. E. Marshak, Phys.Rev. D **39**, (1989) 693 ;
K.S. Babu and R. N. Mohapatra, Phy.Rev.Lett. **63**, (1989) 938 ;
X.G. Hi, G.C. Joshi, H.Lew, B.H.J. Mckellar and R.R.Volkas, Phy.Rev.D **40**, (1989) 3140

[9] A. Abbas, Phys.Lett. **238B**, (1990) 344

[10] A. Abbas, J.Phys. **16G**, (1990) L163

[11] A. Abbas, Nuovo Cim. **106A**, (1993) 985

[12] T. Pradhan, Nuovo Cim. **38**, (1965) 883 ;
V.N. Gribov, Nucl.Phys. **206B**, (1982) 103;
A.S.Gorsky, B.L.Jaffe and A. Yu. Khodjamirian, Phy.Lett. **227B**, (1989) 474